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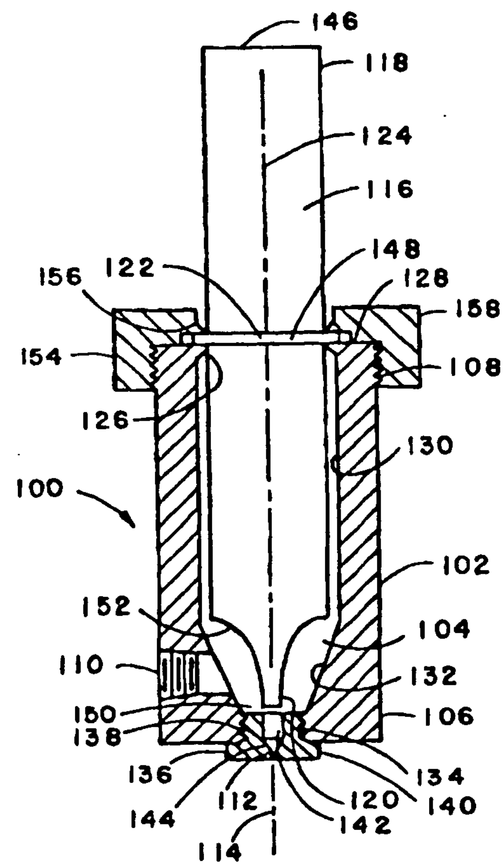
(54) Title: ULTRASONIC LIQUID FUEL INJECTION APPARATUS AND METHOD

(57) Abstract

An ultrasonic apparatus and a method for injecting a pressurized liquid fuel by applying ultrasonic energy to a portion of the pressurized liquid fuel. The apparatus (100) includes a die housing (102) which defines a chamber (104) adapted to receive a pressurized liquid and a means for applying ultrasonic energy (16) to a portion of the pressurized liquid. The die housing (102) further includes an inlet (110) adapted to supply the chamber with the pressurized liquid, and an exit orifice (112) defined by the walls of a die tip (136). The exit orifice (112) is adapted to receive the pressurized liquid from the chamber (104) and pass the liquid out of the die housing (102). When the means for applying ultrasonic energy (116) is excited, it applied ultrasonic energy to the pressurized liquid without applying ultrasonic energy to the die tip (136). The method involves supplying a pressurized liquid to the foregoing apparatus (100), applying ultrasonic energy to the pressurized liquid but not the die tip (136) while the exit orifice (112) receives pressurized liquid from the chamber (104), and passing the pressurized liquid out of the exit orifice (112) in the die tip (136).



ULTRASONIC LIQUID FUEL INJECTION APPARATUS AND METHOD

Background f the Invention

The present invention relates to an ultrasonic liquid fuel injection apparatus. The present invention also relates to a method of ultrasonically injecting liquid fuel.

Summary of the Invention

The present invention provides an ultrasonic apparatus and a method for injecting a pressurized liquid fuel by applying ultrasonic energy to a portion of the pressurized liquid fuel so that the liquid fuel can be injected into an internal combustion engine. The apparatus includes a die housing which defines a chamber adapted to receive a pressurized liquid fuel and a means for applying ultrasonic energy to a portion of the pressurized liquid fuel. The die housing includes a chamber adapted to receive the pressurized liquid fuel, an inlet adapted to supply the chamber with th pressurized liquid fuel, and an exit orifice (or a plurality of exit orifices) defined by the walls of a die tip and adapted to receive the pressurized liquid fuel from the chamber and pass the liquid fuel out of the die housing. Th means for applying ultrasonic energy is located within the chamber and may be, for example, an immersed ultrasonic horn. According to the invention, the means for applying ultrasonic energy is located within the chamber in a manner such that no ultrasonic energy is applied to the die tip (i.e., the walls of the die tip defining the exit orifice).

In one embodiment of the ultrasonic fuel injector apparatus, the die housing may have a first end and a second end and the exit orifice is adapted to receive the pressurized liquid fuel from the chamber and pass the pressurized liquid fuel along a first axis. The means for applying ultrasonic energy to a portion of the pressurized liquid fuel is an ultrasonic horn having a first end and a second end. The horn is adapted, upon excitation by ultrasonic energy, to have a node and a longitudinal mechanical excitation axis. The horn

plurality of exit orifices) defined by the walls of a die tip, the exit orifice being adapted to receive the pressuriz d liquid from the chamber and pass the liquid out of the die housing. Generally speaking, the means for applying ultrasonic energy is located within the chamber. For example, the means for applying ultrasonic energy may be an immersed ultrasonic horn. According to the invention, the means for applying ultrasonic energy is located within the chamber in a manner such that no ultrasonic energy is applied to the die tip (i.e., the walls of the die tip defining the exit orifice).

In one embodiment of the present invention, the die housing may have a first end and a second end. One end of the die housing forms a die tip having walls that define an exit orifice which is adapted to receive a pressurized liquid from the chamber and pass the pressurized liquid along a first axis. The means for applying ultrasonic energy to a portion of the pressurized liquid is an ultrasonic horn having a first end and a second end. The horn is adapted, upon excitation by ultrasonic energy, to have a node and a longitudinal mechanical excitation axis. The horn is located in the second end of the die housing in a manner such that the first end of the horn is located outside of the die housing and the second end is located inside the die housing, within the chamber, and is in close proximity to the exit orifice.

The longitudinal excitation axis of the ultrasonic horn desirably will be substantially parallel with the first axis. Furthermore, the second end of the horn desirably will have a cross-sectional area approximately the same as or greater than a minimum area which encompasses all exit orifices in the die housing. Upon excitation by ultrasonic energy, the ultrasonic horn is adapted to apply ultrasonic energy to the pressurized liquid within the chamber (defined by the die housing) but not to the die tip which has walls that define the exit orifice.

The present invention contemplates the use of an ultrasonic horn having a vibrator means coupled to the first

the apparatus may be adapted to cavitate a pressurized liquid.

The apparatus and method may be used in fuel injectors for liquid-fueled combustors. Exemplary combustors include, but are not limited to, boilers, kilns, industrial and domestic furnaces, incinerators. The apparatus and method may be used in fuel injectors for discontinuous flow internal combustion engines (e.g., reciprocating piston gasoline and diesel engines).

The apparatus and method may also be used in fuel injectors for continuous flow engines (e.g., Sterling-cycle heat engines and gas turbine engines).

The apparatus and method of the present invention may be used to emulsify multi-component liquid fuels as well as liquid fuel additives and contaminants.

Brief Description of the Drawings

FIG. 1 is a diagrammatic cross-sectional representation of one embodiment of the apparatus of the present invention.

FIG. 2 is an illustration of a device used to measure the force or impulse of droplets in a water plume injected into the atmosphere utilizing an exemplary ultrasonic apparatus.

FIGS. 3-6 are graphical representations of impact force per mass flow of liquid versus distance.

Detailed Description of the Invention

As used herein, the term "liquid" refers to an amorphous (noncrystalline) form of matter intermediate between gases and solids, in which the molecules are much more highly concentrated than in gases, but much less concentrated than in solids. A liquid may have a single component or may be made of multiple components. The components may be other liquids, solid and/or gases. For example, Characteristic of liquids is their ability to flow as a result of an applied force. Liquids that flow immediately upon application of force and for which the rate of flow is directly proportional

the chamber or the means for applying ultrasonic energy can be located entirely within the chamber.

Referring now to FIG. 1, there is shown, not necessarily to scale, and exemplary apparatus for injecting a pressurized liquid fuel into an internal combustion engine. The apparatus 100 includes a die housing 102 which defines a chamber 104 adapted to receive a pressurized liquid fuel. The die housing 102 has a first end 106 and a second end 108. The die housing 102 also has an inlet 110 (e.g., inlet orifice) adapted to supply the chamber 104 with the pressurized liquid. An exit orifice 112 (which may also be referred to as an extrusion orifice) is located in the first end 106 of the die housing 102; it is adapted to receive the pressurized liquid from the chamber 104 and pass the liquid out of the die housing 102 along a first axis 114. An ultrasonic horn 116 is located in the second end 108 of the die housing 102. The ultrasonic horn has a first end 118 and a second end 120. The horn 116 is located in the second end 108 of the die housing 102 in a manner such that the first end 118 of the horn 116 is located outside of the die housing 102 and the second end 120 of the horn 116 is located inside the die housing 102, within the chamber 104, and is in close proximity to the exit orifice 112. The horn 116 is adapted, upon excitation by ultrasonic energy, to have a nodal point 122 and a longitudinal mechanical excitation axis 124. Desirably, the first axis 114 and the mechanical excitation axis 124 will be substantially parallel. More desirably, the first axis 114 and the mechanical excitation axis 124 will substantially coincide, as shown in FIG. 1.

The size and shape of the apparatus of the present invention can vary widely, depending, at least in part, on the number and arrangement of exit orifices (e.g., extrusion orifices) and the operating frequency of the means for applying ultrasonic energy. For example, the die housing may be cylindrical, rectangular, or any other shape. Moreover, the die housing may have a single exit orifice or a plurality of exit orifices. A plurality of exit orifices may be

transducer and the means for applying ultrasonic energy to the multi-component liquid.

The application of ultrasonic energy to a plurality of exit orifices may be accomplished by a variety of methods. For example, with reference again to the use of an ultrasonic horn, the second end of the horn may have a cross-sectional area which is sufficiently large so as to apply ultrasonic energy to the portion of the pressurized liquid which is in the vicinity of all of the exit orifices in the die housing. In such case, the second end of the ultrasonic horn desirably will have a cross-sectional area approximately the same as or greater than a minimum area which encompasses all exit orifices in the die housing (i.e., a minimum area which is the same as or greater than the sum of the areas of the exit orifices in the die housing originating in the same chamber). Alternatively, the second end of the horn may have a plurality of protrusions, or tips, equal in number to the number of exit orifices. In this instance, the cross-sectional area of each protrusion or tip desirably will be approximately the same as or less than the cross-sectional area of the exit orifice with which the protrusion or tip is in close proximity.

The planar relationship between the second end of the ultrasonic horn and an array of exit orifices may also be shaped (e.g., parabolically, hemispherically, or provided with a shallow curvature) to provide or correct for certain spray patterns.

As already noted, the term "close proximity" is used herein to mean that the means for applying ultrasonic energy is sufficiently close to the exit orifice to apply the ultrasonic energy primarily to the pressurized liquid passing into the exit orifice. The actual distance of the means for applying ultrasonic energy from the exit orifice in any given situation will depend upon a number of factors, some of which are the flow rate and/or viscosity of the pressurized liquid fuel, the cross-sectional area of the end of the means for applying the ultrasonic energy relative to the cross-sectional area of the exit orifice, the frequency of the ultrasonic

orifice is in close proximity to the exit orifice but does not apply ultrasonic energy directly to the exit orifice.

An aspect of the present invention covers an apparatus for emulsifying a pressurized multi-component liquid. Generally speaking, the emulsifying apparatus has the configuration of the apparatus described above and the exit orifice is adapted to emulsify a pressurized multi-component liquid when the means for applying ultrasonic energy is excited with ultrasonic energy while the exit orifice receives pressurized multi-component liquid from the chamber. The pressurized multi-component liquid may then be passed out of the exit orifice in the die tip. The added step may enhance emulsification.

The present invention also includes a method of emulsifying a pressurized multi-component liquid. The method includes the steps of supplying a pressurized liquid to the die assembly described above; exciting means for applying ultrasonic energy (located within the die assembly) with ultrasonic energy while the exit orifice receives pressurized liquid from the chamber without applying ultrasonic energy directly to the exit orifice; and passing the liquid out of the exit orifice in the die tip so that the liquid is emulsified.

The present invention covers an apparatus for producing a spray of liquid. Generally speaking, the spray-producing apparatus has the configuration of the apparatus described above and the exit orifice is adapted to produce a spray of liquid when the means for applying ultrasonic energy is excited with ultrasonic energy while the exit orifice receives pressurized liquid from the chamber and passes the liquid out of the exit orifice in the die tip. The apparatus may be adapted to provide an atomized spray of liquid (i.e., a very fine spray or spray of very small droplets). The apparatus may be adapted to produce a uniform, cone-shaped spray of liquid. For example, the apparatus may be adapted to produce a cone-shaped spray of liquid having a relatively uniform density or distribution of droplets throughout the cone-

improve the flow rate and/or improved atomization of the fuel stream as it enters the cylinder. Application of ultrasonic energy appears to improve (e.g., decrease) the size of liquid fuel droplets and narrow the droplet size distribution of the liquid fuel plume. Moreover, application of ultrasonic energy appears to increase the velocity of liquid fuel droplets exiting the orifice into a combustion chamber. The vibrations also cause breakdown and flushing out of clogging contaminants at the exit orifice. The vibrations can also cause emulsification of the liquid fuel with other components (e.g., liquid components) or additives that may be present in the fuel stream.

The apparatus and method may be used in fuel injectors for continuous flow engines such as Sterling heat engines and gas turbine engines. Such gas turbine engines may include torque reaction engines such as aircraft main and auxiliary engines, co-generation plants and other prime movers. Other gas turbine engines may include thrust reaction engines such as jet aircraft engines.

The apparatus and method of the present invention may be used to emulsify multi-component liquid fuels as well as liquid fuel additives and contaminants at the point where the liquid fuels are introduced into the combustor (e.g., internal combustion engine). For example, water entrained in certain fuels may be emulsified so that fuel/water mixture may be used in the combustor. Mixed fuels and/or fuel blends including components such as, for example, methanol, water, ethanol, diesel, liquid propane gas, bio-diesel or the like can also be emulsified. The present invention can have advantages in multi-fueled engines in that it may be used to compatibalize the flow rate characteristics (e.g., apparent viscosities) of the different fuels that may be used in the multi-fueled engine. Alternatively and/or additionally, it may be desirable to add water to one or more liquid fuels and emulsify the components immediately before combustion as a way of controlling combustion and/or reducing exhaust emissions. It may also be desirable to add a gas (e.g., air, N_2O, etc.)

A die tip 136 was located in the threaded opening of the first end. The die tip consisted of a threaded cylinder 138 having a circular shoulder portion 140. The shoulder portion was 0.125 inch (about 3.2 mm) thick and had two parallel faces (not shown) 0.5 inch (about 12.7 mm) apart. An exit orifice 112 (also called an extrusion orifice) was drilled in the shoulder portion and extended toward the threaded portion a distance of 0.087 inch (about 2.2 mm). The diameter of the extrusion orifice was 0.0145 inch (about 0.37 mm). The extrusion orifice terminated within the die tip at a vestibular portion 142 having a diameter of 0.125 inch (about 3.2 mm) and a conical frustrum portion 144 which joined the vestibular portion with the extrusion orifice. The wall of the conical frustrum portion was at an angle of 30° from the vertical. The vestibular portion extended from the extrusion orifice to the end of the threaded portion of the die tip, thereby connecting the chamber defined by the die housing with the extrusion orifice.

The means for applying ultrasonic energy was a cylindrical ultrasonic horn 116. The horn was machined to resonate at a frequency of 20 kHz. The horn had a length of 5.198 inches (about 132.0 mm), which was equal to one-half of the resonating wavelength, and a diameter of 0.75 inch (about 19.0 mm). The face 146 of the first end 118 of the horn was drilled and tapped for a $^{3}/_{8}$-inch (about 9.5-mm) stud (not shown). The horn was machined with a collar 148 at the nodal point 122. The collar was 0.094-inch (about 2.4-mm) wide and extended outwardly from the cylindrical surface of the horn 0.062 inch (about 1.6 mm). Thus, the diameter of the horn at the collar was 0.875 inch (about 22.2 mm). The second end 120 of the horn terminated in a small cylindrical tip 150 0.125 inch (about 3.2 mm) long and 0.125 inch (about 3.2 mm) in diameter. Such tip was separated from the cylindrical body of the horn by a parabolic frustrum portion 152 approximately 0.5 inch (about 13 mm) in length. That is, the curve of this frustrum portion as seen in cross-section was parabolic in shape. The face of the small cylindrical tip was normal to

Example 1

This example illustrates the present invention as it relates to producing a spray of a hydrocarbon oil that may be used as fuel. The procedure was conducted utilizing the same ultrasonic device (immersed horn) as Example 1 set up in the same configuration with the following exceptions:

Two different orifices were used. One had a diameter of 0.004 inch and a length of 0.004 inch (L/D ratio of 1) and the other had a diameter of 0.010 and a length of 0.006 inch (L/D ratio of 0.006/0.010 or 0.6).

The oil used was a vacuum pump oil having the designation HE-200, Catalog # 98-198-006 available from Legbold-Heraeus Vacuum Products, Inc. of Export, Pennsylvania. The trade literature reported that the oil had a kinematic viscosity of 58.1 centipoise (cP) at 104° Fahrenheit and a kinematic viscosity of 9.14 cP at 212° Fahrenheit

Flow rate trials were conducted on the immersed horn with the various tips without ultrasonic power, at 80 watts of power, and at 90 watts of power. Results of the trials are shown in Table 5. In Table 5, the "Pressure" column is the pressure in psig, the "TIP" column refers to the diameter and the length of the capillary tip (i.e., the exit orifice) in inches, the "Power" column refers to power consumption in watts at a given power setting, and the "Rate" column refers to the flow rate measured for each trial, expressed in g/min.

In every trial when the ultrasonic device was powered, the oil stream instantly atomized into a uniform, cone-shaped spray of fine droplets.

Water was metered into the oil stream a by piston metering pump. The pump consisted of a 9/16" diameter by 5" stroke hydraulic cylinder. The piston rod of the cylinder was advanced by a jacking screw driven by a variable speed motor through reduction gears. The speed of the motor was controlled utilizing a motor controller. The water was routed from the cylinder to the third leg of the tee by a flexible hose. The outlet end of the flexible hose was fitted with a length of stainless steel hypodermic tubing of about 0.030" inside diameter which, with the flexible hose installed to the tee, terminated in the approximate center of the oil flow stream (upstream of the ultrasonic device).

The immersed horn device was fitted with the 0.0145" diameter tip. The oil was pressurized to about 250 psig., creating a flow rate of about 35 g/min. The metering pump was set at about 3 rpm resulting in a water flow rate of 0.17 cc/min. Samples of the extrudate (i.e., the liquid output from the ultrasonic device) were taken with no ultrasonic power, and at about 100 watts ultrasonic power. The samples were examined with an optical microscope. The sample that passed through the ultrasonic device while it was unpowered contained widely dispersed water droplets ranging from about 50 - 300 micrometers in diameter. The sample that passed through the ultrasonic device while it received 100 watts of power (i.e., the ultrasonically treated sample) was an emulsion that contained a dense population of water droplets ranging from about 5 to less than 1 micrometer in diameter.

Example 3

This example illustrates the present invention as it relates to the size and characteristics of droplets in a plume of No. 2 diesel fuel injected into the atmosphere utilizing the ultrasonic apparatus described above. Diesel fuel was fed to the ultrasonic apparatus utilizing the pump, drive motor, and motor controller as described above. Tests were conducted at pressures of 250 psig and 500 psig, with and without applied ultrasonic energy.

Table 2

Run	Pressure	Transducer Power	SMD(um)	Velocity(m/s)
1	250 PSIG	0 watts	87.0	33.9
2	250 PSIG	0 watts	86.9	33.6
3	250 PSIG	87.5 watts	41.1	39.2
4	250 PSIG	87.5 watts	40.8	38.2
5	500 PSIG	0 watts	43.4	40.4
6	500 PSIG	0 watts	46.8	41.2
7	500 PSIG	102 watts	41.0	56.3
8	500 PSIG	102 watts	40.9	56.5

As may be seen from the results reported in Table 2, the velocity of liquid fuel droplets may be at least about 25 percent greater than the velocity of identical pressurized liquid fuel droplets out of an identical die housing through an identical exit orifice in the absence of excitation by ultrasonic energy. For example, the velocity of pressurized liquid fuel droplets can be at least about 35 percent greater than the velocity of droplets of an identical pressurized liquid fuel out of an identical die housing through an identical exit orifice in the absence of excitation by ultrasonic energy. Droplet velocity is generally thought to be associated with the ability of a spray plume to penetrate and disperse in a combustion chamber, especially if the atmosphere in the chamber is pressurized.

In addition to affecting droplet velocity, application of ultrasonic energy can help reduce individual droplet size and size distribution. Generally speaking, it is thought that small sized fuel droplets of a relatively narrow size distribution will tend to burn more uniformly and cleanly than very large droplets. As can be seen from Table 2, the Sauter mean diameter of pressurized liquid fuel droplets can be at least about 5 percent smaller than the Sauter mean diameter of droplets of an identical pressurized liquid fuel out of an

Readings were then taken of power in watts, flow rate in raw data, and impact force in grams. The raw data is reported in Table 3.

The data was normalized to represent force in grams per unit of mass flow. The normalized data is reported in Table 4. The normalized data indicate that the addition of ultrasonic energy causes an increase in impact force per mass flow of water. This appears to be directly translatable to an increase in velocity of individual droplets in a spray plume. This normalized data is shown graphically in FIGS. 3 through 6. In particular, FIG. 3 is a plot of impact force per mass flow of water versus distance to target at 400 psig. FIG. 4 is a plot of impact force per mass flow of water versus distance to target at 600 psig. FIG. 5 is a plot of impact force per mass flow of water versus distance to target at 800 psig. FIG. 6 is a plot of impact force per mass flow of water versus distance to target at 1000 psig.

As the pressure in the trials approached 1000 psi. the power delivered by the power supply dropped off drastically, an indication that the ultrasonic assembly had shifted resonance to a point beyond the ability of the power supply to compensate. The impact effect for these trials (i.e., at 1000 psig) was diminished.

Table 4

THRUST/ML/MIN

Pressure 1000 psig

Power	Distance to Target (inches) 1.55	1.45	1.35	1.25	1.15	1.05	0.95	0.85	0.75	0.65	0.55	0.45	0.38
0%	0.185	0.19	0.194	0.197	0.201	0.203	0.206	0.21	0.21	0.207	0.21	0.197	0.2
30%	0.191	0.194	0.196	0.192	0.191	0.19	0.19	0.19	0.2	0.196	0.19	0.194	0.18
50%	0.198	0.191	0.197	0.197	0.192	0.192	0.192	0.19	0.19	0.191	0.18	0.181	0.18

Pressure 800 psig

Power													
0%	0.176	0.175	0.172	0.174	0.178	0.18	0.181	0.18	0.18	0.18	0.17	0.165	0.18
30%	0.178	0.172	0.176	0.178	0.176	0.171	0.174	0.18	0.18	0.178	0.17	0.166	0.17
50%	0.188	0.184	0.19	0.188	0.187	0.188	0.188	0.19	0.19	0.193	0.19	0.179	0.18

Pressure 600 psig

Power													
0%	0.145	0.145	0.141	0.145	0.143	0.145	0.148	0.15	0.15	0.157	0.15	0.145	0.15
30%	0.163	0.173	0.175	0.175	0.173	0.177	0.175	0.18	0.19	0.192	0.19	0.181	0.19
50%	0.163	0.163	0.181	0.184	0.181	0.183	0.183	0.18	0.18	0.184	0.18	0.157	0.17

Pressure 400 psig

Power													
0%	0.12	0.118	0.113	0.12	0.123	0.123	0.12	0.12	0.12	0.12	0.12	0.108	0.11
30%	0.141	0.144	0.148	0.146	0.146	0.139	0.148	0.14	0.14	0.136	0.13	0.12	0.11
50%	0.144	0.141	0.141	0.141	0.144	0.139	0.148	0.15	0.15	0.141	0.13	0.127	0.12

Table 5

Droplet Size

Pressure (psig)	Frequency (kHz)	Volts (volts)	Current (amps)	Watts (calc.)	SMD (um)	50% Size (um)	90% Size (um)
100	19.88	189.9	1.065	202.2	37.61	50.23	83.79
100	19.88	189.9	1.065	202.2	38.48	51.41	86.38
100	0	0	0	0	295.19	355.96	517.05
100	0	0	0	0	301.79	370.29	520.98
200	19.84	223.1	1.058	236.0	25.52	35.32	60.99
200	19.84	223.1	1.058	236.0	26.57	36.32	61.94
200	0	0	0	0	167.38	275.85	492.53
200	0	0	0	0	188.81	261.95	483.32
300	19.83	235.9	1.124	265.1	27.57	39.23	69.68
300	19.83	235.9	1.124	265.1	27.93	39.73	70.56
300	0	0	0	0	135.87	244.13	479.05
300	0	0	0	0	147.80	247.30	480.97
400	19.83	257.4	1.203	309.7	23.74	34.11	61.20
400	19.83	257.4	1.203	309.7	23.74	34.11	61.20
400	0	0	0	0	114.84	234.58	476.21
400	0	0	0	0	110.83	232.97	475.85

(Table 9 - continued)

Pressure (psig)	Frequency (kHz)	Volts (volts)	Current (amps)	Watts (calc.)	SMD (um)	50% Size (um)	90% Size (um)
900	19.82	299.6	1.361	407.8	17.63	29.35	62.29
900	19.82	299.6	1.361	407.8	17.63	29.35	62.29
900	0	0	0	0	27.08	53.62	130.24
900	0	0	0	0	26.89	56.73	146.30
1000	19.82	312.0	1.390	433.7	15.51	29.57	75.74
1000	19.82	312.0	1.390	433.7	15.51	29.57	75.74
1000	0	0	0	0	24.47	54.45	150.39
1000	0	0	0	0	25.03	54.71	147.76

WHAT IS CLAIMED IS:

1. An ultrasonic fuel injector apparatus for injection of liquid fuel into an internal combustion engine, the apparatus comprising:

a die housing defining:

a chamber adapted to receive a pressurized liquid fuel;

an inlet adapted to supply the chamber with the pressurized liquid fuel; and

an exit orifice defined by the walls of a die tip, the exit orifice being adapted to receive the pressurized liquid fuel from the chamber and pass the liquid fuel out of the die housing; and

a means for applying ultrasonic energy to a portion of the pressurized liquid fuel within the chamber without applying ultrasonic energy to the die tip, wherein the means for applying ultrasonic energy is located within the chamber.

2. The apparatus of claim 1, wherein the means for applying ultrasonic energy is an immersed ultrasonic horn.

3. The apparatus of claim 1, wherein the means for applying ultrasonic energy is an immersed magnetostrictive ultrasonic horn.

4. The apparatus of claim 1, wherein the exit orifice is a plurality of exit orifices.

5. The apparatus of claim 1, wherein the exit orifice is a single exit orifice.

6. The apparatus of claim 1, wherein the exit orifice has a diameter of from about 0.0001 to about 0.1 inch.

7. The apparatus of claim 6, wherein the exit orifice has a diameter of from about 0.001 to about 0.01 inch.

8. The apparatus of claim 1, wherein the exit orifice is an exit capillary.

9. The apparatus of claim 8, wherein the exit capillary has a length to diameter ratio of from about 4:1 to about 10:1.

10. The apparatus of claim 1, wherein the ultrasonic energy has a frequency of from about 15 kHz to about 500 kHz.

16. The apparatus of claim 15, wherein the vibrator means is a piezoelectric transducer.

17. The apparatus of claim 15, wherein the vibrator means is a magnetostrictive transducer.

18. The apparatus of claim 17, wherein the piezoelectric transducer is coupled to the ultrasonic horn by means of an elongated waveguide.

19. The apparatus of claim 18, wherein the elongated waveguide has an input:output mechanical excitation ratio of from about 1:1 to about 1:2.5.

20. The apparatus of claim 14, wherein the means for applying ultrasonic energy is an immersed magnetostrictive ultrasonic horn.

21. A method of injecting a pressurized liquid fuel through an orifice, the method comprising:

supplying a pressurized liquid fuel to a die assembly, the die assembly being composed of:

a die housing comprising:

a chamber adapted to receive a pressurized liquid fuel;

an inlet adapted to supply the chamber with the pressurized liquid fuel; and

an exit orifice defined by the walls of a die tip, the exit orifice being adapted to receive the pressurized liquid from the chamber and pass the liquid fuel out of the die housing; and

a means for applying ultrasonic energy to a portion of the pressurized liquid fuel within the chamber;

exciting the means for applying ultrasonic energy with ultrasonic energy while the exit orifice receives pressurized liquid fuel from the chamber, without applying ultrasonic energy to the die tip; and

passing the pressurized liquid fuel out of the exit orifice in the die tip.

22. The method of claim 21 wherein the means for applying ultrasonic energy is located within the chamber.

supplying a pressurized liquid fuel to a die assembly composed of:

a die housing comprising:

a chamber adapted to receive a pressurized liquid fuel; the chamber having a first end and a second end;

an inlet adapted to supply the chamber with the pressurized liquid fuel; and

an exit orifice defined by walls in a die tip and located in the first end of the chamber and adapted to receive the pressurized liquid fuel from the chamber and pass the liquid fuel out of the die housing along a first axis; and

an ultrasonic horn having a first end and a second end and adapted, upon excitation by ultrasonic energy, to have a node and a longitudinal mechanical excitation axis, the horn being located in the second end of the chamber in a manner such that the first end of the horn is located outside of the chamber and the second end of the horn is located within the chamber and is in close proximity to the extrusion orifice;

exciting the ultrasonic horn with ultrasonic energy while the exit orifice receives pressurized liquid fuel from the chamber and without applying ultrasonic energy to the die tip, and

passing the liquid fuel out of the exit orifice in the die tip.

33. The method of claim 32, wherein the exit orifice is an exit capillary.

34. The method of claim 32, wherein the ultrasonic energy has a frequency of from about 15 kHz to about 500 kHz.

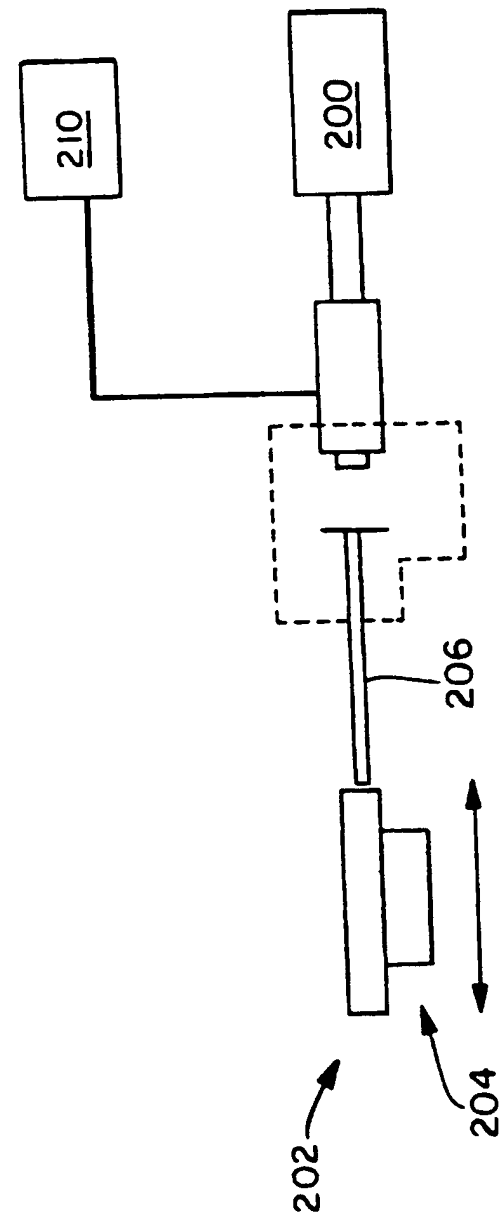


FIG. 2

GRAPH OF IMPULSE PER UNIT FLOW RATE
(800 psi)

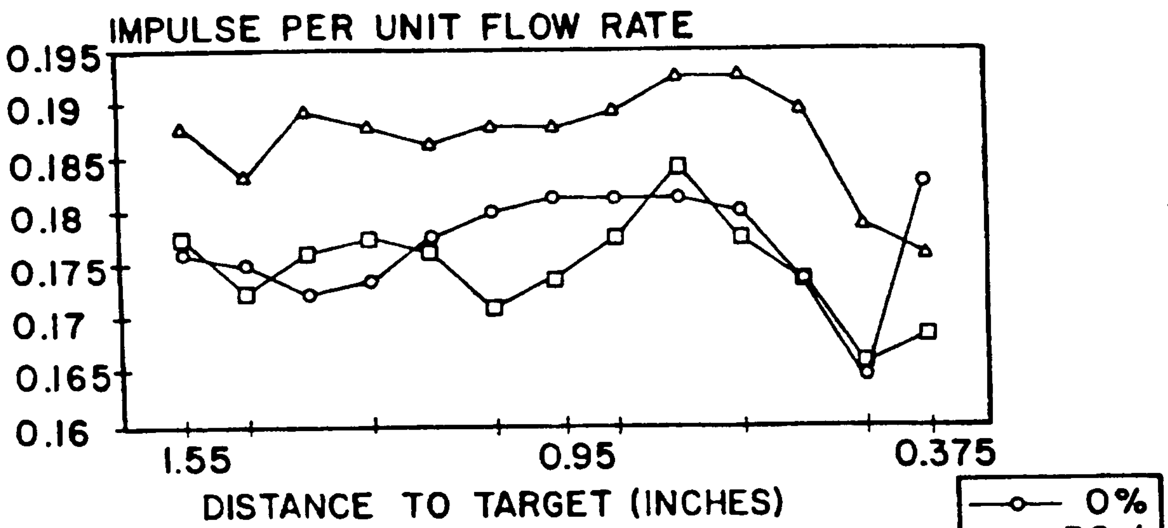


FIG. 5

GRAPH OF IMPULSE PER UNIT FLOW RATE
(1000 psi)

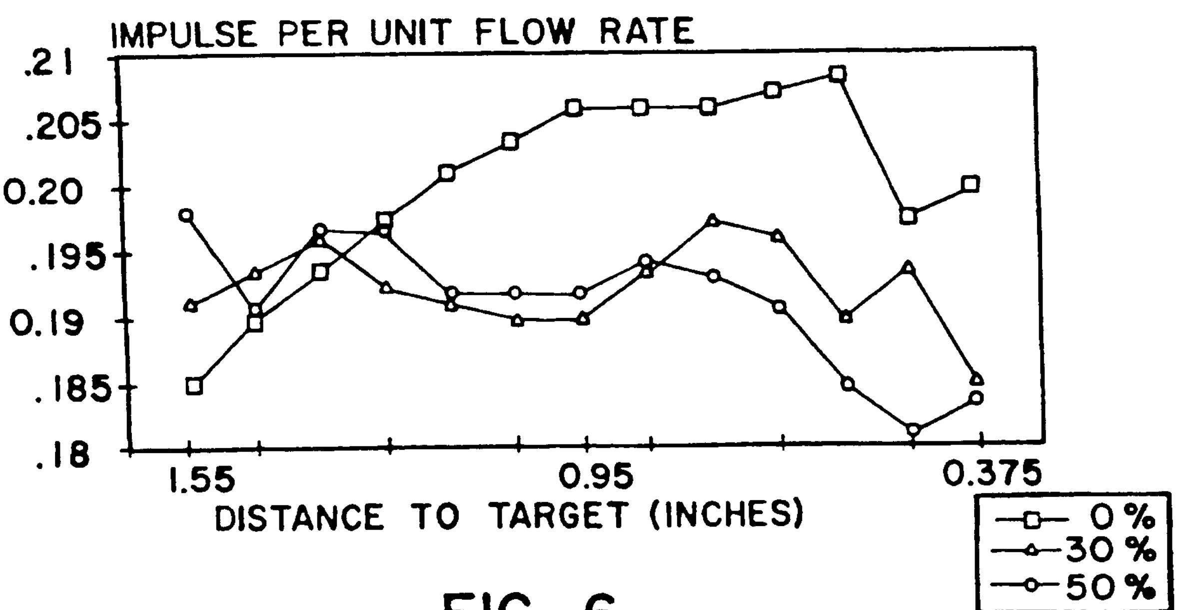


FIG. 6

INTERNATIONAL SEARCH REPORT

Inte onal Application No
PCT/US 96/19206

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